QUARTERLY REPORT

(for July - September 1996)

Contract No. NAS5-31363

OCEAN OBSERVATIONS WITH EOS/MODIS
Algorithm Development and Post Launch Studies

by

Howard R. Gordon
University of Miami
Department of Physics
Coral Gables, FL 33124

Submitted October 15, 1996

I shall describe developments (if any) in each of the major task categories.

1. Atmospheric Correction Algorithm Development.

a. Task Objectives:

During CY 1996 there are four objectives under this task:

(i) Complete development of an algorithm module for removing the effects of stratospheric aerosol and/or cirrus clouds from MODIS imagery over the oceans.

(ii) Conduct research on the effects of strongly absorbing aerosols, and their vertical structure, on the existing atmospheric correction algorithm. Use the results of this research to develop a strategy for their removal.

(iii) Develop a detailed model of the diffuse transmittance of the atmosphere and the manner in which it is influenced by the angular distribution (BRDF) of the subsurface upwelling spectral radiance. Add a module for this to the atmospheric correction algorithm.

(iv) Investigate the effects of ignoring the polarization of the atmospheric light field on the performance of the proposed atmospheric correction algorithm.

b. Task Progress:

(i) None. This task was placed on hold to free time to accelerate Major Task #4 below in response to higher-than-expected MODIS polarization sensitivity in some ocean bands.

(ii) During this quarter, we have tested a "spectral matching algorithm" that, although very slow, is capable of distinguishing between weakly- and strongly-absorbing aerosols. It is based on combining a model of the atmosphere with a water-leaving radiance model for the ocean, and effecting a variation of the relevant parameters until a satisfactory fit to the MODIS top-of-atmosphere radiance is achieved. We believe that the algorithm is also capable of function in the same manner when aerosol vertical structure is an additional parameter. (Note that vertical structure is only important when the aerosol is strongly absorbing.)

(iii) We have completed the study and determined that the BRDF associated with the water-leaving radiance affects the diffuse transmittance in an important manner only for low pigment concentrations and then only in the blue. Otherwise, the residual error from removal of the path radiance is more significant than the BRDF-induced error.

(iv) Completed.

c. Anticipated Activities During the Next Quarter:

(i) We will complete the conceptual structure of a cirrus cloud correction algorithm, and begin writing the implementation software.

(ii) We will carry out further studies of the performance of the spectral matching algorithm. We will try to increase the speed through utilizing a minimization algorithm, or by preselecting the models to test.

(iii) We will write a software module to accurately compute the diffuse transmittance, and produce the required lookup tables. We envisage delivery of the module by the end of the calendar year.

d. Publications:

H.R. Gordon, Atmospheric Correction of Ocean Color Imagery in the Earth Observing System Era, Journal of Geophysical Research, Atmospheres, (Accepted)

H.R. Gordon, T. Zhang, F. He, and K. Ding, Effects of stratospheric aerosols and thin cirrus clouds on atmospheric correction of ocean color imagery: Simulations, Applied Optics, (Accepted).

H. Yang and H.R. Gordon, Remote sensing of ocean color: Assessment of water-leaving radiance bidirectional effects on atmospheric diffuse transmittance, Applied Optics (In preparation)

2. Whitecap Correction Algorithm.

As described in earlier reports, a whitecap radiometer system has been built and tested to provide a database for developing and validating the whitecap correction algorithm, as well as for providing an estimation of the whitecap contribution to the water-leaving radiance during the post-launch validation phase. The database includes spectral information as well as variables associated with the formation and occurrence of whitecaps such as wind speed and air/sea temperature.

From 29 March to 18 April 1996 the whitecap radiometer system was deployed on the NOAA ship RV Malcolm Baldrige on a cruise from Miami to a test location in the Gulf of Mexico, approximately 70 miles off shore from Cedar Key (Florida) in the Apalachicola Bay. The location provided relatively warm waters (16-17 deg C) with a number of cold fronts moving off the mainland. These fronts usually lasted a couple of days bringing strong winds (sometimes as high as 18 m/s) and lowering the air temperature to about 12 deg C. The occurrence of an unstable atmosphere and good winds provided an interesting spectral whitewater data set.

a. Near-term Objectives:

Our near term objectives in this work are:

(i) Complete the analysis of the data set from the Malcolm Baldrige cruise.

(ii) Fix instrument problems which arose during the Baldrige cruise.

(iii) Acquire another data set to test the results obtained from the Baldrige cruise.

(iv) Prepare publications describing the instrument and the results obtained during this cruise.

b. Task Progress:

(i) We have analyzed much of the cruise data. Interesting effects were found during low sun angle measurements were there was a large enhancement of the reflectance in the red. Although a fall off in the reflectance at 865 nm compared to 670 nm was confirmed, the reflectance was did not fall off as rapidly in the near infrared as had been measured previously in bow foam or surf.

(ii) We have replace connectors which failed during this cruise and improved the sealing of the instrument. The instrument is now ready for another field exercise.

(iii) We are investigating possible cruises in windy sites to acquire more whitecap data to confirm our results to date.

(iv) The publications describing the instrument and the Malcolm Baldrige data set are almost complete.

c. Anticipated Activities During the Next Quarter:

(1) Complete analysis of the RV Malcolm Baldrige data set.

(2) Deploy the whitecap system on another cruise.

(3) Provide our most recent results regarding the spectral variation of whitecap reflectance to R. Evans for inclusion into the atmospheric correction algorithm.

(4) Finish the publications, and also report on the data at the Ocean Optics meeting in Halifax in late October.

d. Publications:

We are preparing two publications on this work. The first is a description of the whitecap radiometer and the second describes the spectrum of the whitecap reflectance. An abstract ``Whitecaps: Spectral reflectance in the open ocean and their contribution to water-leaving radiance,'' by K.D. Moore, K.J. Voss, and H.R. Gordon, has been accepted for presentation at the SPIE Ocean Optics XIII Meeting.

3. In-water Radiance Distribution.

The main objective in this task is to obtain upwelling radiance distribution data at sea for a variety of solar zenith angles to understand how the water-leaving radiance varies with viewing angle and sun angle.

a. Near-term Objectives: None.

b. Task Progress: None.

c. Anticipated Activities During the Next Quarter: Deploy at next feasible opportunity.

4. Residual Instrument Polarization.

The basic question here is: if the MODIS responds to the state of polarization state of the incident radiance, given the polarization-sensitivity characteristics of the sensor, how much will this degrade the performance of the algorithm for atmospheric correction? We have developed a formalism which provides the framework for removal of instrumental polarization-sensitivity effects, and an algorithm for removing much of the error induced by the polarization sensitivity.

a. Near-term Objectives:

The objective is to quantify the influence of uncorrected polarization sensitivity on the MODIS atmospheric correction and pigment algorithms, and to try to understand the accuracy with which instrument characterization must be carried out in order to be able to effect a correction and meet the mission objectives.

b. Task Progress:

We are examining the performance of the algorithm under various scenarios, e.g., high polarization sensitivity and good characterization, high polarization sensitivity and poor characterization, etc.

c. Anticipated Activities During the Next Quarter:

We will continue with the assessment of the polarization-sensitivity induced errors, and prepare a paper for publication that describes the correction algorithm and the sensitivity studies. We will provide a module in the atmospheric correction algorithm to correct for the polarization sensitivity effects based on an adequate pre-launch characterization.

5. Pre and Post-launch Atmospheric Correction Validation and Vicarious Calibration/Initialization.

a. Task Objectives:

The objectives of this task are four-fold:

(i) First, we need to study aerosol optical properties over the oceans to assess the applicability of the aerosol models used in the atmospheric correction algorithm. Effecting this requires obtaining long-term time series of the aerosol optical properties in typical maritime environments. This will be achieved using a CIMEL sun/sky radiometer that can be operated in a remote environment and send data back to the laboratory via a satellite link. These are similar the radiometers used by in the AERONET Network.

(ii) Second, we must be able to measure the aerosol optical properties from a ship during the initialization/calibration/validation cruises. The CIMEL-type instrumentation cannot be used (due to the motion of the ship) for this purpose. The required instrumentation consists of an all-sky camera (which can measure the entire sky radiance, with the exception of the solar aureole region) from a moving ship, an aureole camera (specifically designed for ship use) and a hand-held sun photometer. Our objective for this calendar year is (1) to assemble, characterize and calibrate the solar aureole camera system, (2) to develop data acquisition software, (3) to test the system, and (4) operate it successfully with the all-sky camera.

In the case of strongly-absorbing aerosols, we have shown that knowledge of the aerosol vertical structure is critical. Thus, we need to be able to measure the vertical distribution of aerosols during validation exercises. This can be accomplished with ship-borne LIDAR. We plan to procure a LIDAR system and modify it for ship operations as required.

(iii) The third objective is to determine how accurately the radiance at the top of the atmosphere can be determined based on measurements of sky radiance and aerosol optical thickness at the sea surface. This requires a critical examination of the effect of radiative transfer on ``vicarious'' calibration exercises.

(iv) The forth objective is to utilize data from other sensors that have achieved orbit (MSX), or are expected to achieve orbit (OCTS, POLDER, SeaWiFS) prior to the launch of MODIS, to validate and fine-tune the correction algorithm.

b. Task Progress:

(i) We have been successfully operating the CIMEL instrument on the Dry Tortugas for the last several months. Currently the instrument is being recalibrated at NASA/Goddard, but will be reinstalled in this location when it returns. We are beginning to look at the long term data set from the CIMEL, in particular the sky radiance data, and we anticipate analyzing much of data much more in the coming quarter.

(ii) The sky camera system was been modified and used to make measurements of the sky light polarization at several locations on several occasions. As we shall see in the discussion under (iii), this new polarization capability of the sky camera will be of considerable value in the initialization/ calibration/validation work. During this period we participated in the NASA TARFOX experiment between Bermuda and New York. This cruise took place on a cruise liner, and we participated in three weeks of the cruise effort. The sky camera, with polarization, was operated along with a hand-held sunphotometer and the aureole camera system. While the weather was generally not as good as expected (a hurricane went through while we were on the cruise), there were several clear periods during which we obtained data. We are working on reducing this data at this time, and hope to have the data reduction completed at the end of the next quarter. In addition, we participated in a field exercise with Dennis Clark, using the sky camera, solar aureole system, and sunphotometers during a cruise in Hawaii in September. We will be analyzing this data along with the TARFOX data.

A Micro Pulse Lidar (MPL) system has been ordered from SSEI. It is scheduled for delivery by the end of the quarter.

(iii) As described in our Semi-annual Report, we have completed a study of the accuracy with which one can compute the radiance at the top of the atmosphere from sky radiance measurements made at the sea surface.
The results suggest that the bulk of the error is governed by the uncertainty in the sky radiance measurements. Furthermore, it was shown that the largest error in the radiative transfer process was the error due to the use of scalar radiative transfer theory, and that improvement required the use of vector theory, and thus measurement of the polarization of the sky radiance. We have started to analyze the use of polarization measurements at the surface and believe that the radiative transfer error can be made very small. Furthermore, we are now examining the extent to which the full linear polarization of the top-of-atmosphere radiance can be deduced from surface measurements. This may be very important for validating the pre-launch polarization-sensitivity characterization of MODIS.

(iv) We have been in contact with personnel involved with SeaWiFS, OCTS, and MSX to acquire data formats, and satellite data from these instruments to assess the validity of the atmospheric correction algorithm, and will continue in this effort. We have procured an SGI R10000 Workstation (same chip set and operating system as used by MODIS SDST). This will provide the necessary image processing capability for the pre- and post-launch era.

c. Anticipated Activities During the Next Quarter:

(i) When the CIMEL instrument returns from calibration at NASA we will be installing it in the Dry Tortugas again. We will also begin looking at the long term data that we have been acquiring with this instrument.

(ii) We will be reducing data from the TARFOX cruise and from the most recent cruise in Hawaii. We will also be participating in a cruise off of Hawaii during November with Dennis Clark.

(iii) Continue analysis of the use of polarization measurements at the surface for deducing the full linear polarization of the top-of-atmosphere radiance.

(iv) Port image processing software from Evans' UM/RSMAS in preparation for data from other sensors.

d. Publications:

(i) None.

(ii) None.

(iii) H.R. Gordon and T. Zhang, How well can radiance reflected from the ocean-atmosphere system be predicted from measurements at the sea surface?, Applied Optics (In press).

(iv) None.

6. Detached Coccolith Algorithm and Post Launch Studies (with W.M. Balch)

a. Near-term Objectives:

The algorithm for retrieval of the detached coccolith concentration from the coccolithophorid, E. huxleyi is described in detail in our ATBD. The key is quantification of the backscattering coefficient of the detached coccoliths. Our earlier studies focussed on laboratory cultures to understand factors affecting the calcite-specific backscattering coefficient. A thorough understanding of the relationship between calcite abundance and light scatter, in situ, will provide the basis for a generic suspended calcite algorithm. As with algorithms for chlorophyll, and primary productivity, the natural variance between growth related parameters and optical properties needs to be understood before the accuracy of the algorithm can be determined. To this end, the objectives of our coccolith studies during this last quarter have been to a) perform the last of a series of flow cytometery experiments examining the calcite-specific backscattering coefficient of calcite particles sampled in the field, and b) work up data from our pre-launch cruise in the Gulf of Maine last June.

b. Task Progress:

Background:

To date, the flow cytometry experiments have focussed on calculating the backscattering coefficient for a large variety of biogenic calcite-covered cells. The experiments showed that calcite-specific scattering coefficients changed by almost two orders of magnitude when calculated as the backscattering per unit cell (m2/cell). We hypothesized that if backscattering coefficients of calcite covered cells were calculated per unit mass calcite, then the backscattering coefficient would be much less variable, regardless of species.

The issue that we have faced was to measure the calcite-specific backscattering coefficient for pure biogenic calcite particles. Recall that in the previous flow cytometer experiments, we showed that calcite-specific bb* of plated coccolithophores had low variance contrary to the anomalous diffraction predictions for b*. The limitation of this experiment was that the flow cytometer could only sort plated coccolithophore cells, where we gated on chlorophyll a fluorescence and side scatter. Thus, the cell sorts contained both particulate organic and inorganic matter, not pure calcite. The instrument still could not sort non-fluorescing, scattering particles, free from organic matter. This was particularly obvious in our measurements of the calcifying dinoflagellate, Thoracosphaera sp, in which the presence of cellular protoplasm in the calcite thecae significantly altered the scattering coefficient of the cell. Therefore, the definitive experiment still had to be done in which light scattering of pure coccolith suspensions was examined. This required major enhancements of our analytical abilities, both in the flow cytometry and the calcite detection.

We ran a series of flow cytometer experiments prior to this summer's experiments at Bigelow Laboratory. The goal of the experiments was to sort individual coccoliths with the flow cytometer, to measure the volume scattering properties of the sorts, then to measure the mass of calcite within the sort. Sorting of individual coccoliths is not trivial with the flow cytometer due to their small size and lack of autofluorescence, and it required careful tuning of the instrument so that we could sort coccoliths based on the ratio of horizontally- and vertically-polarized forward light scattering. Moreover, this work required much more precise measurements of calcium concentration, heretofore never made on these calcifying algal species. This was particularly difficult when one considers that seawater (and flow cytometer sheath fluid) has Ca++ concentrations in excess of 10 mM. We have access to a graphite furnace atomic absorption spectrometer, with three orders of magnitude more sensitivity (50 pg Ca ml-1) than flame atomic absorption. The instrument, a Perkin Elmer Model 5100PC, belongs to Dr. Larry Mayer at the Darling Center, University of Maine (Walpole, ME). My technician, Dave

Drapeau, took the Perkin Elmer course in Atlanta, GA in order to process the samples. As an example of the experiments, we sorted 100,000 coccoliths of Emiliania huxleyi (2mm diameter) with the flow cytometer. This translated to ~25 ng C or 83 ng Ca, which, in a 5 mL final volume, gave a concentration of 16.6 ng Ca ml-1 (still sufficient to give a signal to noise ratio 300 on the graphite furnace atomic absorption spectrometer).

Species of calcifying algae (both coccolithophores and Thoracosphaera heimii, the calcifying dinoflagellate) were purchased from the Provasoli-Guillard Culture Collection (at Bigelow Laboratory), and grown in K media. Cultures were kept in the temperature-controlled rooms at Bigelow on a 14h:10h light:dark cycle and harvested in logarithmic growth phase for sorting with the EPICS V flow cytometer with multi-parameter data acquisition. Calcite particles then were sorted based on their birefringence under the laser light. Polarizing filters were placed, at right angles, on the two forward-angle scatter detectors of the flow cytometer (Olson et al. ,1989). Olson showed that the ratio of horizontally to vertically polarized forward light scatter was about 3.0 for calcite particles and 1.0 for all other particle types (we have found a ratio closer to 12 for coccoliths using the Bigelow Laboratory flow cytometer). This proved highly effective for discriminating and sorting calcite particles.

We performed the necessary set-up, cell counts and cell sorting for five calcifying algal species (which required that we start our culturing activities at least 2.5 weeks prior to the beginning of the experiment). Two species, Syracosphaera sp.and Coccolithus pelagicus grew in clumps which caused problems in sorting individual coccoliths. The other three species, E. huxleyi (clone 89E), Cricosphaera sp., and Thoracosphaera sp. were adequate for our experiments. We spent two days of our week of flow cytometer time tuning the flow cytometer for sorting individual coccoliths and verifying that flow cytometer counts versus regular cell counts were in good agreement. This was absolutely critical to our final results. One aspect that allowed this work to proceed more rapidly than previous experiments, however, was that there was no need to sort plated cells since the goal was to define the backscattering coefficient per mg of calcite carbon. We calibrated our laser light scattering photometer using an isotropic scattering standard supplied with the instrument, and frequently checked for any instrument drift with ultra-clean distilled water.

The results showed that, indeed, the coccolith specific backscattering coefficients were highly variable. Comparisons of bb particulate versus the concentration of Ca demonstrate much less variance than the coccolith-specific values. The best-fit average calcite-specific bb* value for these data was 11.7 m2 (mol C)-1 (std dev=+/- 3.2m2 (mol C)-1). Equally noteworthy, was the fact that the calcite-specific bb* based on pure sorts of coccoliths was about an order of magnitude higher than the values based on plated cells (thus containing both organic and inorganic matter). Our previous results in which plated coccolithophores were sorted gave calcite-specific bb* values averaging about 0.6 m2 mol C-1(std dev=+/- 0.36 m2 mol C-1). The presence of absorbing organic matter obviously reduced the quantity of scattered light detected by the scatterometer; such an observation only serves to emphasize the importance of preparing pure coccolith suspensions in order to determine their bb*.

The confirmation of low variance in the calcite-specific bb* for a wide range of particle sizes has significant ramifications for the remote sensing of suspended calcite. Simply put, the results suggest that for remote reflectance measurements of calcite, one need not know the species (particle type) responsible in order to calculate the suspended load of calcite within about 25% accuracy. If our results had shown more species-specific variance in bb*, then one would have had to know the type of particle in order to calculate the amount of suspended calcite. Moreover, our results showed that bb* values were less size dependent than the b* values (predicted from anomalous diffraction calculations on calcite spheres).

Work performed this quarter:

We performed the last phase of this flow cytometry work this August, in which we sorted natural calcite particles sampled from ships of opportunity from all over the world ocean. Calcite particles were sorted using polarizing filters placed at right angles over the two forward-angle scatter detectors of the EPICS flow cytometer, and gating based on the ratio of the two polarized forward angle scattering signals. This work provided a more representative estimate of the backscattering coefficient for naturally-occuring calcite particles, rather than cultured coccolithophores. This work was required to verify that coefficients measured with cultures apply to the field.

The experiment went much more smoothly than we ever expected, especially given the difficulties of sorting field coccoliths from detritus. Moreover, the results are very encouraging. Arabian Sea samples that contained Gephyrocapsa sp. coccoliths -- this is a globally ubiquitous species, not available in culture and never specifically sampled in our light-scattering studies -- showed similar backscattering coefficients to Emiliania huxleyi. While the atomic absorption measurements have not yet been processed yet to determine the concentration of suspended calcite, the particle specific coefficients look quite reasonable. We still have one day of flow cytometer time left, and intend to sort coccoliths that we sampled in the Gulf of Maine this year.

We also continued the processing of our cruise data from this year's pre-launch Gulf of Maine work. These activities included:

1) microscopic cell and coccolith enumeration at about 80 samples per month (this work is extremely laborious but necessary in order to know the abundance of coccoliths in samples that we measured backscattering);

2) processing graphite furnace samples to calculate the concentration of suspended calcite; and

3) processing calcification rate estimates which allow us to calculate turnover times of the suspended calcite.

c. Anticipated Activities During the Next Quarter

We will process the atomic absorption samples from last quarter's flow cytometer experiment, and process all of the data to calculate calcite specific backscattering coefficients.

We are scheduled to do another pre-launch cruise to the Gulf of Maine in November. We will be measuring calcite-dependent backscattering continuously, as well as suspended calcite concentration, cell and coccolith counts, and calcification measurements.

OTHER DEVELOPMENTS

The bulk of the PI's effort during this reporting period was focused on three activities. The first was the preparation of revisions of the Water-leaving Radiance and Coccolith concentration ATBD's. These revisions were completed and delivered to the EOS Senior Project Scientist in August 15, 1996. The second was a detailed revision of the MOCEAN Validation Plan on behalf of the Group. This occurred after attending the MODIS Ocean Group (MOCEAN) Meeting in July. The third was participation in the MCST audit of progress toward the Level 1B algorithm in the VIS/NIR bands on September 5, 1996.